Ultrafast All-Optical Switching with a Single Quantum Dot

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Abstract: We demonstrate all-optical switching based on a single quantum dot coupled to a photonic crystal cavity. The quantum-dot mediated interaction between the signal and control beams occurs at the single-photon level.

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The system of a single quantum dot (QD) coupled to a photonic crystal is attracting growing interest because of the potential in quantum and classical information processing, and as a testbed for experiments in quantum optics. We recently showed that a single QD can control the amplitude and phase, and even the photon number statistics of the cavity reflectivity[1, 2, 3]. It was also shown that the QD saturates when the intracavity photon number exceeds unity[1, 4]. This giant optical nonlinearity offers an attractive means for all-optical switching. In this contribution, we present theoretical predictions and experimental results of all-optical switching based on the giant optical nonlinearity. We show that a control beam switches the transmissivity of a signal beam, where both the signal and control beams have low intensities corresponding to intracavity photon numbers near unity. We demonstrate switching duration shorter than 50 ps.

The structure consists of a linear three-hole defect cavity fabricated in a GaAs slab whicih contains a single layer of randomly distributed InAs QDs, as described in [1]. In Fig. 1(a,b), we present a cavity which is strongly coupled to a single quantum dot, which has an estimated dipole decay rate $\gamma/2\pi < 1$GHz. A fit yields the cavity field decay rate $\kappa/2\pi = 24$GHz and cavity-dot coupling rate $g/2\pi = 27$GHz; since g exceeds the decoherence rates, the cavity/dot system is strongly coupled.

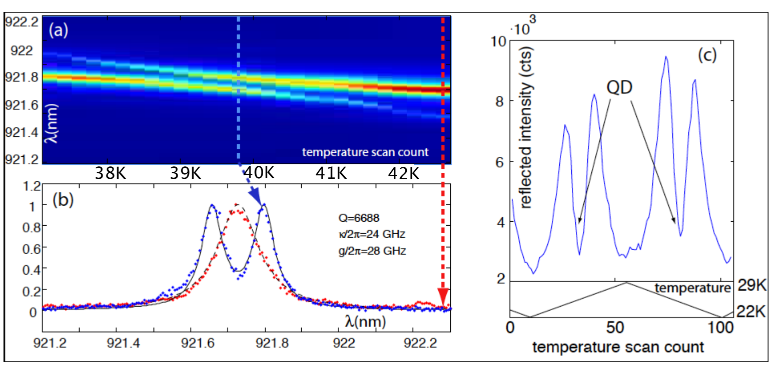

Fig. 1. Characterization of quantum dot/cavity strong coupling. (a) Photoluminescence spectra as the QD is tuned through the cavity resonance by temperature. (b) Cavity spectrum when the dot is resonant and off-resonant with it, showing the split cavity spectrum (blue) and bare cavity (red). (c) Reflected intensity at low cw-signal power.

A continuous-wave laser is coupled into the cavity and represents the 'signal' beam, and a second pulsed (40-ps) beam can be added as the 'control' beam. The reflected signal beam shows a large QD-induced dip in the cavity reflectivity (Fig. 1(c)) as a result of coherent scattering from the quantum dot[1]. For maximum nonlinearity in the signal beam reflectivity, we align both the dot and the signal beam on resonance with the cavity.

To estimate the time-resolved reflectivity of the cavity, we measure the reflected intensity when the control and signal beams are applied separately vs. simultaneously. Any difference arises due to the nonlinearity of the system. First only the control beam is switched on with a power of $I_c = 3$nW. A 20-second integration

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on a streak camera is shown in Fig. 2(a). Then the cw-signal beam is also coupled into the cavity at a power of 600 nW (Fig. 2(b)). Fig. 2(c) plots the difference between (b) and (a), yielding the nonlinear response of the QD/cavity system. In Fig. 2(d), we show the averaged nonlinear response when the measurement was repeated eight times (black crosses), where individual scans were shifted slightly to correct for streak camera timing drift.

These time-resolved switching measurements are fit by a stochastic solution to the master equation: the cavity reflectivity was simulated with the control beam only, and then with the control and continuous-wave signal beams on simultaneously. The difference matches the experimentally measured nonlinear intensity transmission. The nonlinear response, shown in green in Fig. 2(d), matches the experiment well.

Our complete measurements indicate that this QD/cavity system allows optically controlled switching on the time scale of the modified dot bandwidth $g^2/\kappa > 100$GHz, and at an intracavity photon number near unity (Fig. 2(d)). Using the phase measurement technique described in Ref.[2], not only the intensity, but also the phase of the signal beam can be controlled by the pulsed control beam. The ultrafast amplitude and phase control of signal photons via resonant or detuned control photons is promising for applications that include photon number detection by cross-phase modulation, two-qubit quantum gates, and ultrafast all-optical switching in optical communications.

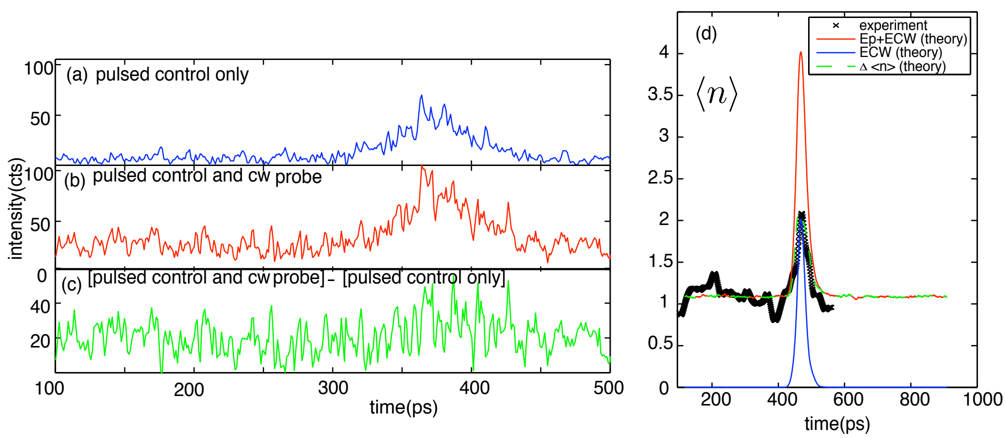

Fig. 2. (a) Measured reflectivity of pulsed control beam only, integrated over 20 seconds. (b) Measured reflectivity of control beam and signal beams. (c) Nonlinear response given by difference between (a) and (b). (d) Average of eight integration cycles (black crosses). Also shown are fits by stochastic master equation. The vertical axis is deduced from the fit to the saturation behavior of the cw-signal beam.

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